Charge Stripes in High-T_c Superconductors

One-Dimensional Structures Raise New Questions

One of the great unsolved problems of contemporary condensed-matter physics is the origin of superconductivity in the "high-temperature" superconductors (HTSCs). With a puzzling array of properties unlike those of ordinary superconductors, these materials have defied understanding since the discovery of the first HTSC compound in 1987. Now, a collaboration comprising researchers from Stanford University, the University of Tokyo, and the ALS has published evidence from angle-resolved photoelectron spectroscopy at the ALS for perhaps the most surprising behavior yet, the self-assembling of charge carriers into spatially localized, one-dimensional stripes. While the stripes were already known from other work, the latest data raises new questions about the electronic structure associated with these entities and its relation to superconductivity.

Angle-resolved photoelectron spectroscopy (ARPES) probes the electronic structure (energy and momentum) of materials by measuring the energy and angle of the emitted electrons. In particular, ARPES can determine in "momentum space" the Fermi surface which represents the locus of the momenta of the highest energy occupied electron states (Fermi energy). The Fermi surface is important because electrons near the Fermi surface are responsible for many physical properties, including superconductivity. From high-resolution measurements along the Fermi surface in HTSCs, ARPES has revealed several major departures from the behavior of conventional superconductors.

For their ARPES experiments, the researchers studied a compound known to have stripes, $(La_{1.28}Nd_{0.6}Sr_{0.12})CuO_4$, whose "parent" compound, La_2CuO_4, is an insulator. Copper and some of the oxygen atoms are arranged on a square lattice in parallel planes with little interplanar interaction. Replacing some of the lanthanum in the insulator with strontium (strontium doping), which has one less electron for bonding, to form $(La_{2-x}Sr_x)CuO_4$ results in the generation of positively charged holes (missing electrons) that end up in the copper-oxygen planes. Over a strontium concentration range (x) from around 6 to 27 percent, the material becomes superconducting, except at 12 percent where the superconductivity is suppressed.

Stripes, in which holes are confined to parallel lines of copper atoms in the copper-oxygen planes separated by insulating regions without holes, were first observed at this so-called one-eighth doping, suggesting a perhaps antagonistic, but in any case intimate, relationship between superconductivity and stripe formation. The replacement of some lanthanum with neodymium stabilizes the stripes at low temperature. Stripes were later seen at other dopings and in other superconductors.

The ARPES spectra obtained for $(La_{1.28}Nd_{0.6}Sr_{0.12})CuO_4$ exhibited several unusual features. The Fermi surface implied by the data is highly one dimensional. It has a cross-like shape consisting of two sets of parallel lines that intersect at right angles. This pattern deviates significantly from that calculated for the two-dimensional copper-oxygen planes but is consistent with the superposition of Fermi surfaces from stripes with two perpendicular orientations. The one dimensionality seems to imply that the electrons are well confined in the stripes and move along them. However, the data also indicate that electrons very close to the Fermi energy show two-dimensional behavior, i.e., electrons can also move perpendicular to the stripes. The unusual behavior of the stripes may represent a new state of matter and apparently a new theory is called for to understand this behavior.

These results provide new grist for the HTSC mill, whose implications may reach farther than even superconductivity. The several families of HTSCs constitute one segment of a still larger class of so-called strongly correlated materials that are characterized by a powerful Coulomb repulsion between neighboring electrons. Many physicists believe that solution of the HTSC problem will require a new paradigm for strongly correlated materials.

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X. J. Zhou, P. Bogdanov, S. A. Kellar, T. Noda, H. Eisaki, S. Uchida, Z. Hussain, and Z.-X. Shen, "One-Dimensional Electronic Structure and Suppression of *d*-Wave Node State in $(La_{1.28}Nd_{0.6}Sr_{0.12})CuO_4$," *Science* **286** (1999) 268.

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- **High-temperature superconductivity an unsolved problem**
  - *Puzzling array of properties measured by many different techniques*
  - *A new paradigm for such strongly correlated materials needed*

- **Charge stripes observed previously in $(La,Nd,Sr)_2CuO_4$ compounds**
  - *Charge carriers in Cu-O planes separate into parallel conducting lines*
  - *Stripes possibly competing with superconductivity*

- **Angle-resolved photoelectron spectroscopy (ARPES)**
  - *Determine energy band structure (energy as a function of momentum)*
  - *Measure Fermi surface (locus of momenta of highest energy occupied electron states)*
  - *High-T_c superconductors require high energy and momentum resolution*

- **ARPES of $(La_{1.28}Nd_{0.6}Sr_{0.12})CuO_4$ at ALS**
  - *Cross-shaped Fermi surface consistent with stripes*
  - *Evidence for both one- and two-dimensional behavior*
  - *Theoretical framework for understanding not in hand*

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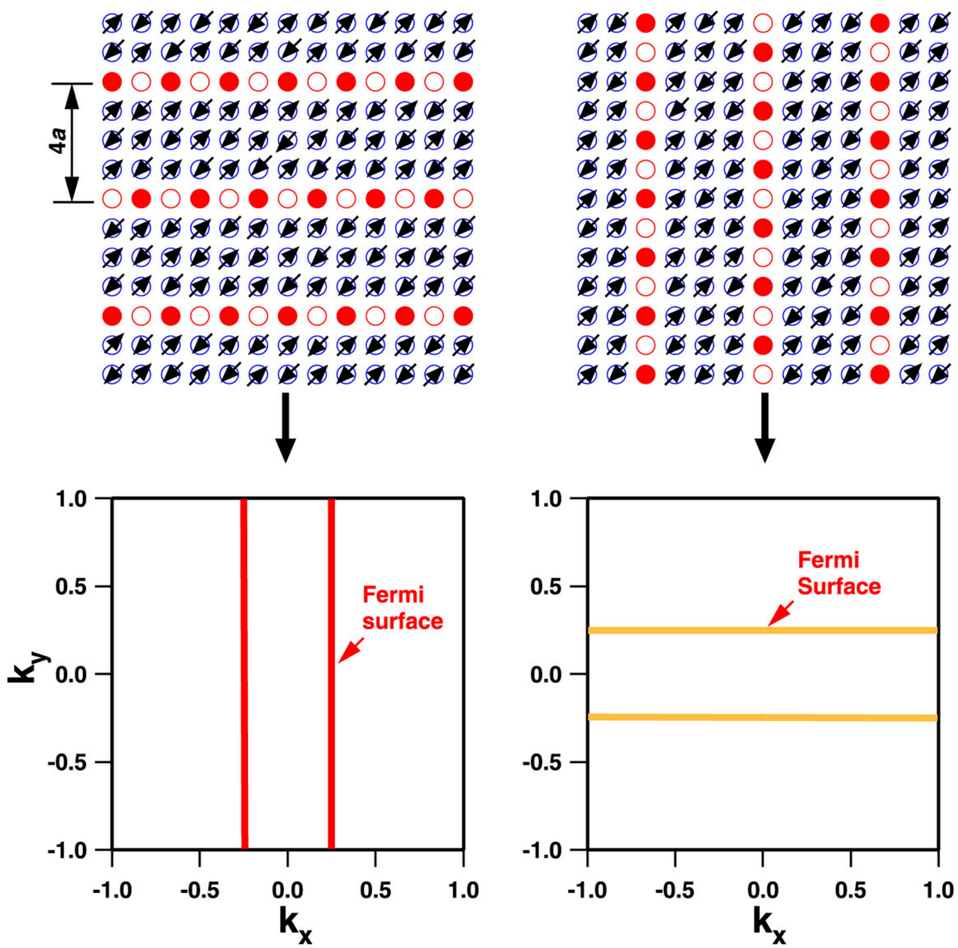

Models showing two orientations of charge stripes in the Cu-O planes and the associated Fermi surfaces for momentum (k) in the x and y directions. Up and down arrows represent local magnetic moments in the antiferromagnetic insulator that separates the stripes. Red circles in stripes represent holes.

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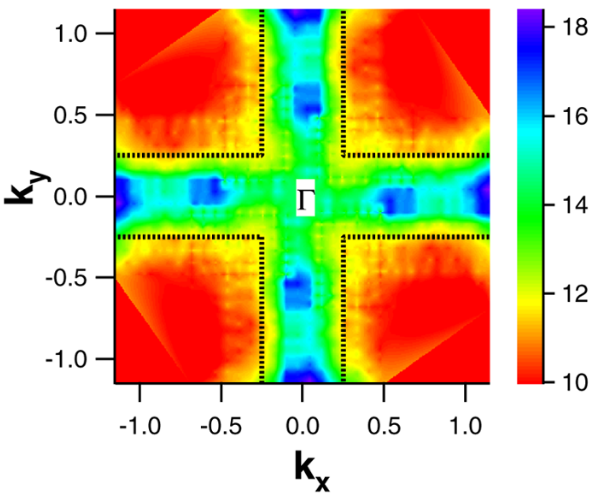

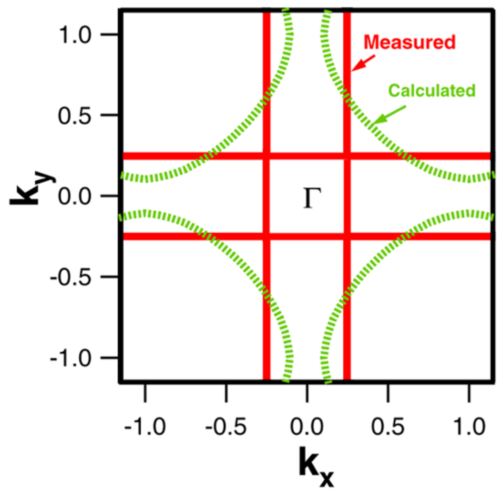

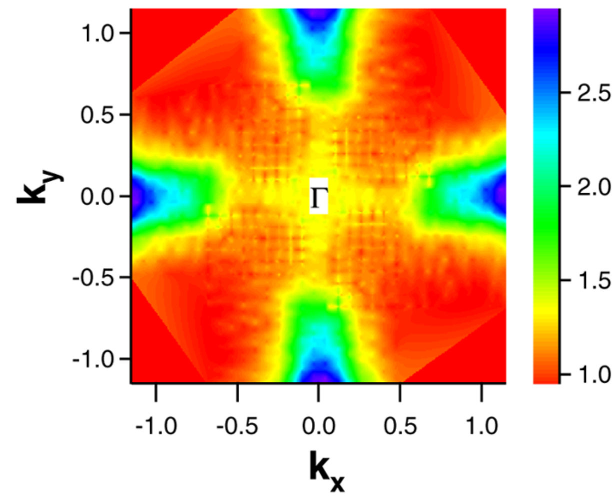

Integrating the photoemission intensity over a 500-meV range of energies near the Fermi energy is a way to visualize the Fermi surface, defined as the boundary between high and low integrated intensities (blue is high; red is low).

The Fermi surface determined in this way is consistent with a superposition of the Fermi surfaces of one-dimensional perpendicular stripes but differs significantly from that calculated for the two-dimensional Cu-O planes.

The reduced intensity at low momenta when integrating over a narrower range (100 meV) reveals an anisotropic energy gap. Low-energy excitations across the gap indicate electrons close to the Fermi energy also have two-dimensional behavior.

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